

# METHOD AND CONTROL DEVICE FOR OPERATING A MILL TRAIN FOR METAL STRIP

## CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is the US National Stage of International Application No. PCT/EP2004/011171, filed October 6, 2004 and claims the benefit thereof. The International Application claims the benefits of German Patent application No. 10346274.0 filed October 6, 2003. All of the applications are incorporated by reference herein in their entirety.

## FIELD OF THE INVENTION

[0002] The invention relates to a method; one application is particularly suitable for operation in a hot-rolling mill, e.g. in the finishing train, but is not restricted to this.

[0003] The invention also relates to a control device.

## BACKGROUND OF THE INVENTION

[0004] It is known from the unexamined German application DE 198 51 554 A1 that the profile and/or flatness of a metal strip is determined at the discharge point of a mill train and is used to preset a mill train. The measured visible flatness is supplied here to a neural network in the form of input parameters.

[0005] A flatness regulating system for metal strip is known from DE 197 584 66 A1, with a method being employed to measure the surface geometry of hot-rolled strip by generating lines on the surface of the strip. The visible flatness measured in this manner is supplied to a flatness regulator via a flatness analysis system.

## SUMMARY OF THE INVENTION

[0006] The object of the invention is to operate a mill train for metal strip such that a control is provided to ensure that a required visible flatness of the rolled metal strip is complied with in a reliable and sufficiently accurate manner within predefined limits.

[0007] The object is achieved by a method of the type mentioned above, with values for the visible flatness being translated into values for the intrinsic flatness using a strip shape model to control the roll stands and a material flow model being used to determine the intrinsic flatness – looked at in the material flow direction – before a physical point for measuring flatness.

[0008] The claimed possibility of taking into account both the visible flatness of the mill train and the intrinsic flatness with the aid of the strip shape model means that extremely stringent requirements can be complied with in respect of the quality of the visible flatness of the metal strip, even though the visible flatness or waviness of the metal strip sometimes completely disappears during rolling under tension, i.e. between the roll posts, and cannot therefore be measured in practice in many instances within the mill train. By translating values for the visible flatness into values for the intrinsic flatness or values for the intrinsic flatness into values for the visible flatness, intrinsic strip flatness values calculated using the material flow model and visible strip flatness values measured at the discharge point of a mill train can be brought into line with each other or verified

[0009] The strip shape model is used first to establish a unique relationship between the intrinsic and visible flatness of the metal strip. It is then possible for the first time not just to carry out presettings on the basis of flatness measurements but also to use the visible flatness for accurate control or regulation of the ongoing rolling process.

[00010] The visible flatness is advantageously determined in the form of a strip shape pattern. The strip shape pattern is easy to compare in respect of data and can be stored with relatively little outlay.

[00011] The strip shape pattern is advantageously three-dimensional.

[00012] At least one of the variables wavelength, amplitude and phase offset of the individual tracks is advantageously evaluated in addition to the relative length of individual tracks of the metal strip to determine the strip shape pattern of the metal strip. The strip shape pattern can thus be identified much more accurately.

[00013] A multi-track laser measuring device is advantageously used to determine the strip shape pattern, allowing economical identification of the strip shape pattern with a sufficiently high level of precision.

[00014] The visible flatness is advantageously measured topographically. This makes surface identification of the surface structure of the strip and in particular of the strip shape pattern directly possible.

[00015] The flatness values are advantageously translated online. This allows particularly precise control or regulation of the strip flatness.

[00016] The flatness values are advantageously translated with the aid of an real-time-capable approximation function. This can save on-line computing time during the translation between visible and intrinsic flatness.

[00017] The strip shape pattern of the metal strip is advantageously modeled using the strip shape model by applying a fictitious temperature distribution in the transverse direction of the metal strip based on the intrinsic flatness of the metal strip. The thermal expansion in the longitudinal direction of the strip, but not however in the transverse direction, corresponding to this strip temperature distribution corresponds to a length distribution that can be assigned to the intrinsic flatness. Only one segment of limited length must therefore be modeled and the model equations for elastic plate deformations with major deflections can be worked out with suitable edge conditions at the segment edges.

[00018] One or more flatness limit values are advantageously predefined at freely selectable points within and/or after the mill train in order to control the mill train. The flatness limit values can relate to the intrinsic flatness and/or the visible flatness. Because flatness limit values can be predefined everywhere within or after the mill train, regulation accuracies for the rolling process can be significantly increased.

[00019] The object is also achieved by a control device for operating a mill train for metal strip with at least one roll stand, with the control device for implementing a method described above having at least one regulating unit coupled to a strip shape model, which is coupled to a device for measuring the visible flatness of the metal strip and to a material

flow model. Advantageous embodiments of the control device are specified in the subclaims. The advantages of the control device are similar to those of the method.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[00020] Further advantages and details will emerge from the description which follows of an exemplary embodiment in conjunction with the figures, in which:

FIG 1 shows a multi-stand mill train for rolling metal strip and a control device assigned to the mill train,

FIGs 2a-2c show examples of metal strip with flatness errors,

FIG 3 shows the division of a metal strip into tracks,

FIG 4 shows a section of a multi-stand mill train with a control device,

FIG 5 shows the geometry of a section of a metal strip.

#### DETAILED DESCRIPTION OF THE INVENTION

[00021] According to Figure 1 a mill train for rolling a metal strip 1 is controlled by a control processor 2. The metal strip 1 can for example be a steel strip, an aluminum strip or a non-ferrous metal strip, in particular a copper strip. The mill train has at least two roll stands 3.

[00022] The roll stands 3 have at least working rolls 4 and - as shown in Figure 1 for one of the roll stands 3 - generally also back-up rolls 5. The roll stands 3 could have even more rolls, for example intermediate rolls that can be displaced axially.

[00023] The metal strip 1 passes through the mill train in its longitudinal direction x, with the transverse direction y of the metal strip being largely parallel to the axes of the working rolls 4.

[00024] The mill train shown in Figure 1 is configured as a finishing train for hot-rolling steel strip. The present invention is particularly suitable for use with a multi-stand

finishing train for hot-rolling steel strip but is not restricted to this. The mill train could in particular also be configured as a cold-rolling mill train (tandem train) and/or for rolling a non-ferrous metal (e.g. aluminum, copper or another non-ferrous metal).

[00025] The control device 2 has a regulating unit 11. This in turn has a module 10 for profile and flatness control, which is coupled to a material flow model 9. The control device 2 predefines target values for profile and flatness control elements (not shown here) to the stand regulators 6. The stand regulators 6 then adjust the control elements according to the predefined target values.

[00026] The input variables supplied to the control device 2 include for example pass schedule data such as the input thickness of the metal strip 1 and a roll force and draft reduction per pass for each roll stand 3. The input variables generally also include an end thickness, a target profile value, a target thickness contour and a target flatness pattern of the metal strip 1 at the discharge point of the mill train. The rolled metal strip 1 should generally be as flat as possible.

[00027] However the metal strip 1 often has flatness errors, as shown by way of an example and schematically in Figures 2a, 2b and 2c. Flatness errors of the metal strip 1 can be measured at one point  $x_2$ , as shown in Figure 1, for example using a multi-track laser measuring device 13.

[00028] Figure 2a shows centric surface irregularities or waves in the metal strip 1. Figure 2b shows flatness errors at the edges of the metal strip 1. Figure 2c shows waves in the metal strip 1, which occur repeatedly in the longitudinal direction  $x$  of the metal strip 1 and in two areas in particular in the transverse direction  $y$  of the metal strip 1.

[00029] The bulges in the metal strip 1 are caused in particular by internal stresses in the metal strip 1. Internal stresses in the metal strip are also referred to as intrinsic strip flatness ip.

[00030] Figure 3 shows the division of a metal strip 1 into fictitious tracks  $S_1$  to  $S_n$  or into measuring tracks  $S'_1$  to  $S'_m$ . If the metal strip 1 were to be cut up into narrow longitudinal strips or into tracks  $S_1$  to  $S_n$ , it would be possible to measure an uneven strip

length distribution (the intrinsic strip length distribution), which is the cause of the internal stresses in the metal strip 1. The multi-track laser measuring device 13 captures the relative length of the metal strip 1 for each measuring track S1' to Sm' and preferably also determines variables such as wavelength, amplitude and/or the phase offset of the individual tracks S1' to Sm'. It is important that the associated intrinsic or measured relative lengths do not correspond for corresponding fictitious tracks S1 to Sn and measuring tracks S1' to Sm'.

**[00031]** As shown in Figure 4, a distinction is made between intrinsic strip flatness ip and visible strip flatness vp when hot-rolling metal strip 1. The intrinsic strip flatness ip refers, as mentioned above, to the strip length distribution over the tracks S1 to Sn. The visible flatness vp results from the wave behavior of the strip, which is for example a function of variables such as strip thickness, strip width, the elasticity module of the metal strip 1 and the overall tension to which the metal strip 1 is subjected.

**[00032]** According to Figure 4 the visible flatness vp is measured at one point x2 at the discharge point of the mill train, in particular a finishing train, and supplied to a strip shape model 12. The visible flatness vp is measured according to the invention such that not only is the visible strip length distribution over the strip width in the transverse direction y an output variable of a measuring device but the three-dimensional strip shape pattern of the strip can also be reconstructed from the measuring device output variables. In the case of a multi-track laser measuring system therefore not only the (relative) length of the individual measuring tracks S1' to Sm' is output by the measuring device but also wavelength and phase offset for each track S1' to Sm'. With a topographic measurement of the visible flatness vp the surface structure of the metal strip 1 is captured at the surface and three-dimensionally over large areas of the metal strip 1. A topographic strip flatness measurement is preferably based on a strip projection method. Strip patterns are thereby projected onto the surface of the metal strip 1 and continuously captured with the aid of a matrix camera.

**[00033]** The intrinsic flatness ip is preferably calculated at a point x1 between or after the roll stands 3, in particular between and/or after the roll stands 3 of a finishing train. The calculation is thereby preferably made using a material flow model 9 (see Figure 1), which is preferably part of a regulating unit 11. The intrinsic flatness ip calculated by the material flow model 9 can be compared with the measured visible flatness vp with the aid of the strip shape model 12 at one point x2 at the discharge point of the mill train, at which the visible

flatness vp is measured. In the case of a cold-rolling mill in particular it would essentially also be possible to measure the intrinsic flatness ip on the metal strip 1.

**[00034]** The strip shape model 12 allows a unique relationship to be established between intrinsic flatness ip and visible flatness vp, as far as possible. Thus for example with a very thick metal strip 1 with moderate intrinsic lack of flatness it is not possible to conclude the intrinsic flatness ip from the strip shape behavior, as such a metal strip 1 generally does not bulge.

**[00035]** The various flatness values (ip and vp) are preferably determined in the following sequence:

1. The visible flatness vp, which generally corresponds to the waviness behavior of the metal strip 1, is generally measured after a last roll stand 3, for example at the discharge point of a finishing train.
2. The strip shape model 12 is used to determine the intrinsic flatness ip of the metal strip 1 at the point for measuring the visible flatness vp (see step 1).
3. The material flow model 9 is used to determine the intrinsic flatness ip between the roll stands 3, for example within the finishing train. The intrinsic flatness can therefore be determined before the physical point for measuring flatness, in this instance intrinsic flatness, looked at in the material flow direction.

**[00036]** The relationship between an intrinsic flatness ip between the roll stands 3 and an intrinsic flatness ip after the last of the roll stands 3 is established using the material flow model 9. Input variables such as the strip thickness contours of the metal strip 1 as well as flatness patterns or flatness values before and after passage through a roll stand 3 can be supplied to the material flow model 9. The material flow model 9 determines the intrinsic flatness pattern of the metal strip 1 online after passage through the roll stand 3 as well as a roll force pattern in the transverse direction y of the metal strip 1 and supplies it to a roll deformation model (not shown in more detail here). The roll deformation model (not shown in more detail here) is preferably part of a regulating unit 11. The roll deformation model

determines roll deformations and supplies them to a target value determination unit (not shown in more detail here), which uses the determined roll deformations and a contour pattern of the metal strip 1 on the stand discharge side to determine the target values for the profile and flatness control elements in each individual roll stand 3.

**[00037]** Use of the strip shape model 12 allows the material flow model 9 and the profile and flatness control implemented in the module 10 (see Figure 1 in each instance) to be adjusted based on the measured data for visible flatness vp. Upper and lower limits can be specified for the visible flatness vp or for the corresponding visible lack of flatness of the strip and these limits can be translated with the aid of the strip shape model 12 into limits for the intrinsic flatness ip or intrinsic lack of flatness. The strip shape model 12 uses the intrinsic lack of flatness to calculate the waviness pattern of the metal strip 1. The calculated waviness pattern can be used in turn to determine the visible lack of flatness. Inverse modeling is used for the converse conclusion.

**[00038]** The strip shape model 12 is preferably based on the theory of elastic plate deformation. The intrinsic flatness ip is modeled by applying a fictitious strip temperature distribution over the strip width, i.e. in the transverse direction y, resulting in thermal expansion in the longitudinal direction x of the metal strip 1 and at the same time to the length distribution associated with the intrinsic flatness ip.

**[00039]** Let us look now at a strip segment of length a, width b and thickness h as shown in Figure 5. The drawing also shows the longitudinal direction x, transverse direction y and a perpendicular z. Only a strip segment with a length of a half or whole basic wave length and with periodic edge conditions at the top and bottom ends of the strip segment is modeled. The edge conditions at the sides of the strip are free edges. The model equations are partial differential equations and the associated edge conditions, which can be solved for example using finite difference methods or finite element methods.

**[00040]** The strip shape model 12 can be used directly in real-time as a function of the computing time of the solution algorithm. Alternatively an offline model can be used to generate an real-time-capable approximation function, which is then used in real-time for the strip shape model 12.

[00041] To understand the mode of operation of the strip shape model 12 better, it first has to be acknowledged that when hot-rolling a metal strip 1 for example, the measured deflections of the metal strip 1, which are due to the bulging of the metal strip 1, are generally significantly larger than the strip thickness  $h$ . They are however typically significantly smaller than both the typical wavelength of the strip shape behavior and also the strip width  $b$ . While the traditional, linear theory of plate deformation only applies when the deflections are less than or equal to approximately 1/5 of the strip thickness  $h$ , in the present instance a non-linear description of the plate warp must be used. In addition to the variables shown in Figure 5, which describe the metal strip 1, the elasticity module or e-module for short is also used, with a constant e-module generally being assumed. The non-linear strip shape behavior can now be described as follows:

$$[00042] \quad (I) \frac{D}{h} \bullet \nabla^4 w(x, y) = \frac{p}{h} + L(w(x, y), \Phi(x, y))$$

[00043] Forces operating in the plane of the strip are thereby expressed in the form of a potential  $\Phi$ , also referred to generally as Airy's stress function.  $w$  refers to the vertical displacement of the metal strip 1 while  $p$  describes the pressure distribution operating from outside, which acts in the perpendicular  $z$ .  $D$  is defined by the equation below:

$$(II) D: = \frac{Eh^3}{12(1-\nu^2)}$$

[00044]  $E$  thereby stands for the e-module and  $\nu$  stands for the Poisson's ratio of the metal strip 1.

[00045] The following also applies for the term  $L(w, \Phi)$  from equation (I):

$$(III) L(w, \Phi): = \frac{\partial^2 w}{\partial x^2} \frac{\partial^2 \Phi}{\partial y^2} - \frac{\partial^2 w}{\partial y^2} \frac{\partial^2 \Phi}{\partial x^2} - 2 \frac{\partial^2 w}{\partial x \partial y} \frac{\partial^2 \Phi}{\partial x \partial y}$$

[00046] If assumptions are now made in respect of internal stresses and strains due to thermal causes, the following results:

(IV)

$$\frac{1}{E} \cdot \nabla^4 \Phi(x, y) + K_x \frac{\partial^2 T(x, y)}{\partial y^2} + K_y \frac{\partial^2 T(x, y)}{\partial x^2} = \left( \frac{\partial^2 w}{\partial x \partial y} \right)^2 - \frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial y^2} = -\frac{1}{2} L(w(x, y), w(x, y))$$

[00047]  $T$  thereby refers to the temperature in the metal strip 1 and  $K_x$  or  $K_y$  the coefficient of thermal expansion in the longitudinal or transverse direction ( $x$  or  $y$ ).

[00048] The equations (I) and (IV) form a system of two coupled, non-linear, partial differential equations. If suitable edge conditions are now inserted, for example free edges or periodical edge conditions at the top and bottom ends of a strip segment, the equations (I) and (IV) can be solved numerically in an iterative manner.

[00049] The basic concept of the invention can be summarized as follows:

[00050] The invention relates to a method and a control device for operating a mill train for metal strip 1, having at least one roll stand 3, with the intrinsic flatness  $ip$  of the metal strip 1 being determined at the discharge point of the mill train. To ensure compliance with a required visible flatness  $vp$  of the rolled metal strip 1 within predefined limits in a reliable and sufficiently accurate manner, it is proposed that the visible flatness  $vp$  or strip shape behavior of the metal strip 1 be determined or preferably be measured at the discharge point of the mill train and be translated into the intrinsic flatness  $ip$  of the metal strip 1 using a strip shape model 12. The visible flatness can thus be used in real-time with the aid of the strip shape model 12 to control the roll stands of the mill train. According to the invention the visible flatness  $vp$  can be better regulated preferably online throughout the mill train with the aid of the strip shape model 12.

[00051] The strip shape model 12 is real-time-capable and establishes a unique relationship between the absolute intrinsic flatness  $ip$  of the rolled metal strip 1 and the actual measured visual defects in the metal strip 1, in other words the visible flatness  $vp$ . It is possible for the first time to verify, adjust and coordinate a material flow model 9 based on the intrinsic flatness or its corresponding profile and flatness control in respect of the actual measured values.